Avian UV/violet cones as magnetoreceptors

The problem of separating visual and magnetic information

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In a recent paper, we described the localization of cryptochrome 1a in the retina of domestic chickens, *Gallus gallus,* and European robins, *Erithacus rubecula*: Cryptochrome 1a was found exclusively along the membranes of the disks in the outer segments of the UV/violet single cones. Cryptochrome has been suggested to act as receptor molecule for the avian magnetic compass, which would mean that the UV/V cones have a double function: they mediate vision in the short-wavelength range and, at the same time, magnetic directional information. This has important implications and raises a number of questions, in particular, how the two types of input are separated. Here, we point out several possibilities how this could be achieved.

Radical Pair Processes Underlie the Avian Magnetic Compass

A 'magnetic compass' is widespread among birds—it has been demonstrated in numerous species of passerines,[1] but also in homing pigeons[2] and domestic chickens.[3] The respective directional information in birds is mediated by radical pair processes[4-8] in the eye.[9-11] Cryptochrome, a blue light absorbing pigment, has been suggested as receptor molecule,[4] because it is the only photopigment known to occur in animals that has the required properties. Cryptochrome had been found in the eyes of birds[12-15] (reviewed in ref. 16), but its precise location in the retina was not known.

In our recent paper,[17] we have demonstrated Cry1a at the disk membranes in the outer segment of the UV/V single cones.

Association with the membranes means that the various Cry1a molecules within one receptor cell are probably arranged to act as a unit, and the rather even distribution of the UV/V single cones across the entire hemispherically-shaped retina[17,18] indicates that these receptor cells could be oriented in the various spatial directions. Hence the yields of the radical pair processes can form a specific magnetically-induced pattern on the retina that is centrally symmetric with respect to the magnetic vector, allowing birds to obtain directional information. In short, the arrangement of Cry1a in the UV/V cones appears to fulfil the requirements of the Radical Pair model,[4] which supports the idea that Cry1a is the receptor molecule for the avian magnetic compass.

Why is Cry1a Expressed in the UV/V Cones?

We found Cry1a exclusively expressed in the UV/V cones—why is it not located in one of the other spectral cone types or in the rods? In birds, the UV/V cones are integrated fully in a tetrachromatic color system as suggested by behavioral studies[19] and by the fact that UV/V cones contribute their inputs to color coding ganglion cells projecting to the brain in vertebrates ranging from turtles[20] to mammals.[21] Two possible reasons for expressing Cry1a in the UV/V cones come to mind: first, these cones possess transparent oil droplets[22,23] that allow the short wavelengths activating the cryptochrome[24,25] to reach the outer segments, while the other cones with opsins tuned to longer wavelengths have

colored oil droplets[22,23] filtering out these wavelengths. Second, the UV/V cones are a low density population and comprise the smallest proportion of the cones, about 10% depending on species.[18,26,27] As the magnetic field-induced activation pattern has smooth and gradual transitions (see below), a low-density detector system is sufficient to detect these signals. Hence the evolutionary choice of the UV/V cones could have economic reasons. The rods would also fulfill the first criterion because they have no light-filtering oil droplet, but they would not be an economic alternative, because they comprise up to 40% of the photoreceptors even in chickens and other diurnal bird species;[26,28,29] nocturnal birds have heavily rod-dominated retinae (e.g., up to 96% rods in different owls).[30] Furthermore, because of the high light sensitivity of rods, their response to light would possibly dominate any magnetic response too strongly.

The UV/V receptors in birds thus contain two types of photopigments, namely the UV- or V-sensitive SWS1-opsin that is affected by light but not by the magnetic field, and additionally the cryptochrome that absorbs blue light[31] and is modulated by its changing alignment with respect to the direction of the geomagnetic field. The level of activation of the UV/V cones therefore depends on the incident light falling on the UV-opsin as well as on the activation of the cryptochromes, i.e., it represents visual as well as magnetic information. Behavioral data suggest that the reception of magnetic directions is largely independent of the activation of the UV/V opsin—it occurs under UV light that activates the UV opsin as well as under monochromatic green light that does not activate this opsin.[32] There are no indications that the UV cones have two separate outputs for the opsin-induced and the cryptochrome-induced signals. Rather, on the neuronal level, the activation of the Cry1a molecules would be combined with that of the UV/V opsin to a single output of the UV/V sensitive cone.

Separating Visual and Magnetic Input

Since the UV cones are integrated in the avian tetrachromatic color system,[19,20] they cannot be considered as separate processing units specialized for the perception of magnetic directional information. Instead, in the course of further processing, the two components of the combined signal must be separated to obtain the respective information. This has been considered a problem,[33] leading to speculations that the activation by bright daylight might override or mask the magnetic compass information. It has been suggested that the radical pair mechanism in night-migrating passerines might be a special development of that group, with a second mechanism existing for magnetoreception during the day. This, however, appears to be rather unlikely. In directional training tests during daytime, radio frequency fields disrupt magnetic compass orientation in chickens[7] and zebra finches,[8] indicating the same radical-pair processes as in night-migrating passerines.[6,7] Also, the location of cryptochrome along the disks of the UV/V cones in chickens and robins is very similar and did not vary in the course of the day.[17] These findings suggest the same primary processes in day-active and night-migrating birds. Hence birds must have mechanisms to separate visual and magnetic input, either directly at the retinal level or more centrally.

The idea of an extraction of the magnetic information already at the retinal level is attractive, and the retinal network as such is complex enough to allow any sort of speculation on potential mechanisms. The easiest way would be a comparison of the output of adjacent UV/V cones with and without cryptochrome, because in this case the visually induced activation of both cones should be identical. However, there is no evidence for a pairing of UV/V cones,[26] and our study[17] shows that Cry1a is present in every UV/V cone. Likewise, comparison with the β band of the other color cone pigments, which has a maximum at UV to V wavelengths, is not possible because these are most probably masked by colored oil droplets.[22,23,30] The only possibility is a comparison between the activation of the UV/V cones and the blue cones, as the absorbance profiles of the two receptors overlap around 400 nm. Hence wavelengths in this range that activate both receptors to a certain degree (or a wavelength not activating any of the two receptors) should be helpful to allow a separation of the two types of input because changes in the visual signal should be synchronous, whereas the magnetic signal occurs only in the UV-cones. Such calculations could already be performed at the retinal level and be transferred to the brain by color-opponent ganglion cells. At least in the turtle retina, three types of color-opponent ganglion cells have been described reacting to UV/V stimuli with excitation and to blue stimuli with inhibition or vice versa.[20] Too strong asymmetry of activation by the visual stimulus, however, could hamper such a comparison.

Separation at Higher Processing Levels

Separating the two types of input could also take place at a higher processing level. Within the brain, the first candidates for processing of complete retinal images, as needed for extraction of the magnetic information, would be areas containing a topographic retinal projection. Two such retinotopic maps have recently been described in reference 34, one within the *optic tectum*, the first station of the tectofugal visual system, and another one within the visual Wulst, the telencephalic station of the thalamofugal visual system. For both these areas, there are indications for an involvement in the reception of magnetic directional information: early electrophysiological recordings showed responses to changes in the direction of the magnetic field,[35,36] and a subdivision of the Wulst, 'Cluster N', which is most probably identical with the area which processes visual information,[37] is activated during magnetic orientation.[33,37,38]

In principle, birds could extract magnetic information from neuronal maps using static images as well as movement information. Processes based on the static image could use the different composition of the activation patterns, i.e., the different spatial frequency distributions of the visual image and of the magnetic field input. While the visual image contains a wide range of spatial frequencies, with high and medium frequencies, e.g., strong local contrasts and sharp edges, magnetic information is characterized by low spatial frequencies, with smooth and gradual

transitions of the activation pattern across the eye. Hence, low pass filtering could be sufficient to separate magnetic information from the visual one. The idea of low pass filtering as a tool to isolate the magnetic field information is supported by the observation that magnetic compass orientation is impaired if vision is blurred by frosted lenses;[39] obviously high spatial frequencies in the visual image are necessary to separate the two information streams.

Birds could also use movement and associated features to separate magnetic from visual input. Each movement induces some image slip on the retina, called optic flow.[40] Translational optic flow is generated when the animal is moving in a straight line. When a bird is moving forward, the images on the retina of the objects in the visual field expand and move from a central toward a lateral position in the visual field when the observer passes by. For the visual pathway that processes the visual feedback of self-motion, translation is thus defined by a globally expanding image. In contrast, the magnetic field-induced pattern maintains the same position and size and can thus easily be distinguished from the visual information.

Processing of optic flow is thought to take place mainly within the so called accessory optic system (reviewed in ref. 41). However, a separation of stationary and moving objects or objects moving with different speed has not been demonstrated as yet for this system. Such mechanisms are known from figure-ground segregation, and neurons solving this task have been found in the optic tectum of birds,[42] which also receives input from the accessory optic system. Neurons within this and probably also higher stations of the tectofugal pathway show differential responses at stimulation by smaller objects with or without a differentially moving or stationary background.[41,43] Thus, the tectofugal system could be a promising candidate for a search for the brain structures separating magnetic field and visual information. It should not be forgotten, however, that there is also evidence suggesting a possible involvement of the thalamofugal visual pathway.[33,37,38] As yet, however, no plausible theory has been presented explaining how the thalamofugal pathway could solve the task.

In summary, the double function of the UV cones as receptors for visual and magnetic information does not seem to be a problem: birds appear to have a variety of possibilities to separate the two types of input. In particular during straight flight, optic flow might be helpful with interpreting magnetic input and deriving compass information.

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